

# **ENTHALPY BY ENERGY BALANCE FOR AERODYNAMIC HEATING FACILITY AT NASA AMES RESEARCH CENTER ARC JET COMPLEX**

T. Mark Hightower  
Experimental Facilities Engineer  
NASA Ames Research Center  
M/S 229-4  
Moffett Field, CA 94035-1000

John A. Balboni  
Group Leader, Arc Jet Development  
NASA Ames Research Center  
M/S 229-4  
Moffett Field, CA 94035-1000

Christine L. Mac Donald  
Engineering Student Intern  
Education Associates Program  
Santa Clara University  
Santa Clara, CA 95053

Karl F. Anderson  
Director of Engineering  
Valid Measurements  
3761 W. Ave. J14  
Lancaster, CA 93536-6304

Edward R. Martinez  
Group Leader, Sensor Technology  
NASA Ames Research Center  
M/S 229-4  
Moffett Field, CA 94035-1000

## **KEYWORDS**

Enthalpy, Energy Balance, Arc Heater, Arc Jet, Resistance Temperature Detector, Anderson Current Loop, Ultrasonic Flow Meter, RTD

## **ABSTRACT**

The NASA Ames Research Center (ARC) Arc Jet Facilities' Aerodynamic Heating Facility (AHF) has been instrumented for the Enthalpy By Energy Balance (EB2) method. Diagnostic EB2 data is routinely taken for all AHF runs. This paper provides an overview of the EB2 method implemented in the AHF. The chief advantage of the AHF implementation over earlier versions is the non-intrusiveness of the

instruments used. For example, to measure the change in cooling water temperature, thin film 1000 ohm Resistance Temperature Detectors (RTDs) are used with an Anderson Current Loop (ACL) as the signal conditioner. The ACL with 1000 ohm RTDs allows for very sensitive measurement of the increase in temperature (Delta T) of the cooling water to the arc heater, which is a critical element of the EB2 method. Cooling water flow rates are measured with non-intrusive ultrasonic flow meters.

## INTRODUCTION

Arc heaters or Arc Jets are flow reactors that use a continuous electric arc discharge in order to produce a plasma flow to simulate the intense conditions of atmospheric entry for ground testing of spacecraft thermal protection materials and systems. (1) Arc heaters have been used and developed at NASA Ames Research Center for this purpose since the 1960s. The arc heater contains the arc and gases with one end sealed and the other open with a nozzle. The inner lining of the arc heater is water-cooled to prevent its destruction from the intense heat. Typically only about 50% of the electrical energy consumed by the arc heater goes into the heating of the gases, with the rest being removed by the cooling water. The enthalpy rise of the test gas can be 20,000 kJ/kg, producing plasma flow temperatures over 6000 K for 30 minute duration.

Accurate determination of the gas enthalpy is one of the most challenging analyses that can be performed on an arc heater run, and there are various methods for doing so. The energy balance method provides a consistent and accurate means to routinely determine the bulk enthalpy of the gas from measurements that are relatively easy to make. The EB2 method relies upon measuring the: voltage and current of the arc to provide the electrical power input; cooling water flow rate and temperature increase to determine the power removed by the cooling water; and the mass flow rates and entering temperatures of the gases being used. By applying the First Law of Thermodynamics (conservation of energy) to these measurements under steady-state operating conditions, the bulk enthalpy of the gas stream leaving the arc heater can be calculated to the accuracy of the instruments used.

The current implementation of the EB2 method in the Aerodynamic Heating Facility (AHF) is summarized below. Finally, the plan to implement the method in other arc heaters at NASA Ames is discussed.

## THE METHOD – ASTM STANDARD

The ASTM standard, “Standard Practice for Measuring Plasma Arc Gas Enthalpy by Energy Balance ASTM Designation: E 341-96” was used for guidance in designing the implementation for the AHF. (2) The method determines Bulk Stagnation Enthalpy at the nozzle exit plane of the arc heater. A steady-state energy balance is performed around the arc heater. The final energy balance is:

$$(\text{Electrical Energy In}) - (\text{Energy Removed by Cooling Water}) = (\text{Energy to the Gas})$$

The method assumes that both energy losses to the surroundings and energy lost to vaporization of inner surface materials are negligible.

In the current implementation, the Delta Enthalpy of the Gas,  $Dh_g$ , is the result reported, rather than the enthalpy of the gas leaving the arc heater,  $h_{go}$ . The reason for this is as follows.  $Dh_g = h_{go} - h_{gi}$ , where  $h_{gi}$  is the enthalpy of the gas entering the arc heater. Since the entering gas is always close to ambient temperature,  $h_{gi}$  is usually about 290 kJ/kg (125 Btu/lbm) for air, where the reference state for all gases is defined to be Internal Energy = 0 at 273.16 K for the saturated liquid. Since this value,  $h_{gi}$ , really does not change much, and the vast majority of arc heater runs produce delta enthalpies of the gas in the many 1000s of kJ/kg, it is not practical to determine  $h_{gi}$  for every run. Therefore,  $Dh_g$  is reported rather than the enthalpy of the gas. The ASTM Standard recognizes this concept on page 3 of the standard, where it states, “Inasmuch as the inlet gas temperature will not differ substantially from room temperature, it will usually have negligible effects on the calculation of total enthalpy.” (2)

## **THE AERODYNAMIC HEATING FACILITY (AHF)**

The AHF Arc Jet is a blow down plasma wind tunnel using one of two arc heaters, each one rated at a maximum input power level of 20 megawatts (MW). From data collection from May 2000 through November 2001, the highest power level used was 12.7 MW with the constricted arc heater (standard configuration), and the lowest power level was 0.39 MW with the Linde (also known as Huels) arc heater, an alternate configuration.

The cooling water flow rate is approximately 250 kg/s. The cooling water supply branches into two supply headers with one on each side of the arc heater. Next to the two supply headers are two corresponding return headers, which join together into a 6 inch schedule 80 pipe where the total exiting cooling water flow rate is measured. One supply/return header pair also provides cooling water supply and return to the test box cooling circuit. The other supply/return header pair also provides cooling water supply and return to the ballast resistor cooling circuit. Due to the branching of the pipe layout and the limited choices where sufficient straight run of pipe would allow flow meters to be installed, it was necessary to also measure the cooling water flow rate to the test box and the temperature of the cooling water leaving the test box, in order to get the data necessary to do the energy balance properly. This will be explained more fully in the Energy Balance section.

## **INSTRUMENTATION DESCRIPTIONS**

### **RESISTANCE TEMPERATURE DETECTORS (RTDs)**

Thin film platinum RTDs of 1000 ohms are used to measure the cooling water temperatures at the outer surfaces of the pipes. The validity of using the pipe surface temperature for the temperature of the water flowing in the pipe is explained in the Pipe Surface Temperature section. These RTDs were each

calibrated by the manufacturer, providing Callendar Van-Dusen constants for each one. For temperatures above 0 °C, the Callendar Van-Dusen equation, expressing the RTD resistance as a function of temperature, takes the form of a quadratic equation.

## ANDERSON CURRENT LOOP (ACL)

An ACL is used as the signal conditioner for the RTDs. An ACL is a device that accurately measures the differences between voltages across resistive elements in a constant current loop. (3,4) NASA has previously used an ACL for the accurate measurement of temperatures with RTDs in wind tunnels. (5) (These references and others on the ACL are readily available over the internet at Valid Measurements' web site, <http://www.vm-usa.com/>.)

The ACL is described with reference to the way that it is configured as shown on Fig. 1 ACL Wiring Configuration diagram. Channels 1, 2, and 3 handle RTDs R1, R2, and R3, which are used to measure temperatures T1, T2, and T3, respectively. T1 is the temperature of the cooling water supply, T2 is that of the cooling water leaving the test box, and T3 is that of the total cooling water leaving in the 6 inch pipe. Channel 1 also serves as the master channel, which is set to provide a constant loop current,  $I_{ex} = 1 \text{ mA}$ , through all of the RTDs.

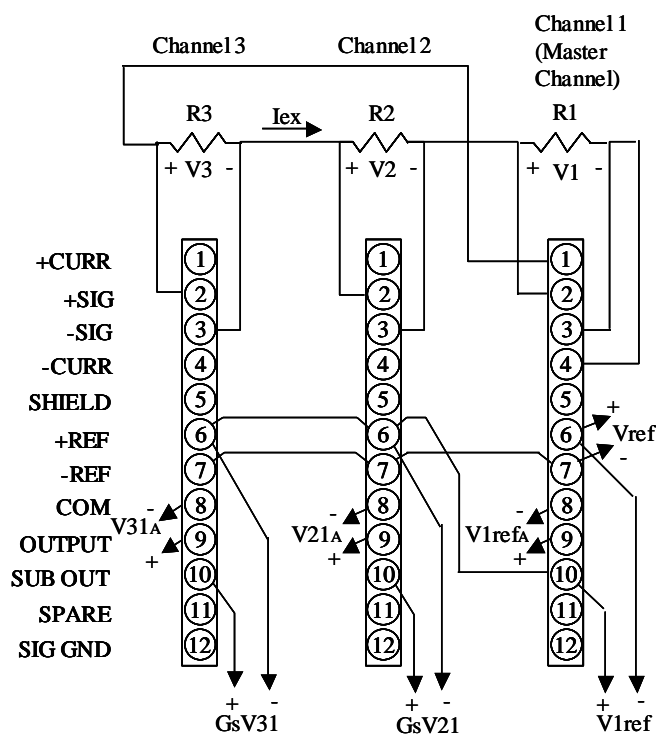
Each Channel has a voltage comparator that outputs the difference of two voltages, the product of the subtractor gain ( $G_s = 2$  for each channel) and the voltage measured minus the reference voltage supplied to the channel. These voltage differences are then amplified further according to the output gains set for each channel,  $G_{o1} = 10$ ,  $G_{o2} = 100$ , and  $G_{o3} = 100$ . Channel 1 compares the product of the subtractor gain ( $G_s = 2$ ) and V1 (the voltage across R1) with Vref, the voltage across the reference resistor. By connecting pin 10 of channel 1 with pin 6 of channel 2 (instead of pin 6 to 6), channels 2 and 3 compare voltages  $G_s V_2$  to  $G_s V_1$ , and  $G_s V_3$  to  $G_s V_1$ , respectively. In this way the output from channel 2 is proportional to the increase in temperature ( $\Delta T$ ) of the cooling water to the test box, and the output from channel 3 is proportional to the overall  $\Delta T$  of the cooling water. The un-amplified outputs from channels 1, 2, and 3, are V1ref,  $G_s V_{21}$ , and  $G_s V_{31}$ , respectively. The amplified outputs from channels 1, 2, and 3, are V1refA, V21A, and V31A, respectively.

The basic equations that describe all of this are shown in Fig. 1. More generalized equations were developed and are actually used in the calculations, based on the accurate calibration of the ACL, where specific values of the subtractor gains and output gains for each channel are used. In this more rigorous approach two intercept correction factors as determined from the calibration are also included for each channel. All of these equations are shown in a Mathcad model, which is available from the author.

## ULTRASONIC FLOW METERS

Ultrasonic flow meters are used to measure the cooling water flow rates at two places, the overall flow leaving in the 6 inch pipe, and the flow to the test box in the 2 inch pipe. Transducers are mounted on the outside of straight runs of pipe. The transducers for both flows are connected to a flow computer,

which outputs the volumetric flow rates. The ultrasonic flow meters operate on the basis of transit-time flow technology. To get the mass flow rates of the water for the energy balance, the volumetric flow rates must be multiplied by the densities of the water at the temperatures where measured. The best linear fit of density versus temperature data for water is used for this purpose.



Master Channel contains Rref and regulates Loop Current, Iex.

Note that this figure is nearly the same as Fig 2-7 in the ACL manual. The only change is connecting pin 10 of channel 1 to pin 6 of channel 2 (instead of pin 6 to pin 6) in order to share GsV1 with channels 2 & 3 (instead of Vref).

R1, R2, and R3 are 1000 ohm RTDs for measuring T1, T2, & T3, respectively.

Rref = 2000 ohm

$G_s = 2 = G_{s1} = G_{s2} = G_{s3}$  (Calibration of unit allows the voltage subtractor gains for each channel to be set the same.)

$I_{ex} = V_{ref}/R_{ref} = 1 \text{ mA}$

$V_{21} = V_2 - V_1$

$V_{31} = V_3 - V_1$

Low Level Outputs

$V_{1ref} = G_{s1} V_1 - V_{ref}$

$G_{sV21} = G_s (V_2 - V_1)$

$G_{sV31} = G_s (V_3 - V_1)$

Amplified Outputs

$V_{1refA} = G_{o1} V_{1ref}$

$V_{21A} = G_{o2} G_s V_{21}$

$V_{31A} = G_{o3} G_s V_{31}$

Where Output Gains are set as follows on the channel boards

$G_{o1} = 10$

$G_{o2} = 100$

$G_{o3} = 100$

FIG. 1 – ACL WIRING CONFIGURATION DIAGRAM

## GAS FLOW SYSTEM

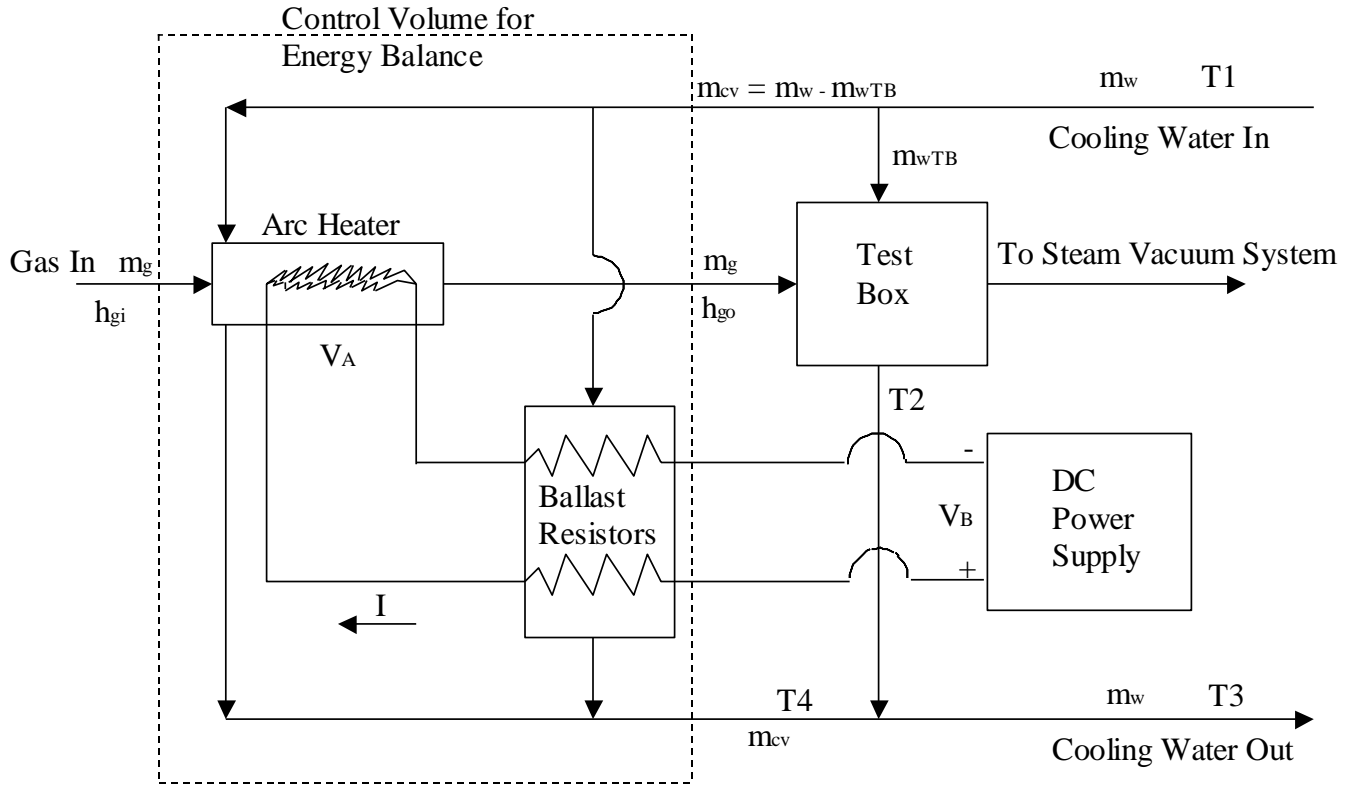
This is an existing system and was not a part of the EB2 installation. It controls and measures the flow rate of all gases used. The data output is in mass flow rate units of g/s.

## ARC VOLTAGE AND CURRENT

These were also existing systems and were not a part of the EB2 installation. Arc voltage and current are both measured, with output in units of volts and amps, respectively.

## ENERGY BALANCE

The Energy Balance equations are described with reference to Fig. 2 Energy Balance Block Flow Diagram. Dotted lines in Fig. 2 outline the Control Volume around which the steady state energy balance is performed.



**FIG. 2 – ENERGY BALANCE BLOCK FLOW DIAGRAM**

In words the energy balance equation is

Increase in Energy (Enthalpy) of Gas = Electrical Energy Into Control Volume – Energy Removed by Cooling Water from Control Volume

$$m_g Dh_g = (V_B I) - (m_{cv} c_p \Delta T_{41}) \quad (1)$$

where

$m_g$  = the total mass flow rate of the gas

$Dh_g = h_{go} - h_{gi}$  = the Delta Enthalpy of the gas

$V_B$  = the voltage across the arc heater and ballast resistors

$I$  = the current to the arc heater

mcv = the mass flow rate of the cooling water to the arc heater and the ballast resistors

cp = the heat capacity of water, assumed constant at 4.19 kJ/(kg K) = 1.0 Btu/(lbm °F)

DDT41 = the increase in temperature of the cooling water to the arc heater and ballast resistors due to the arc heater being on.

$$e_{\text{ArcHandB}} = (VB I - (mcv cp DDT41)) / (VB I) = (mg Dhg) / (VB I) \quad (2)$$

where

$e_{\text{ArcHandB}}$  = the efficiency of the arc heater and ballasts = the energy to the gas divided by the total electrical energy input to the arc heater and ballast resistors

$$Dhg = ((VB I) / (mg)) e_{\text{ArcHandB}} \quad (3)$$

From the above two equations note that the determination of efficiency does not require that mg be measured, whereas the determination of Dhg does require that mg be measured.

$$VB = VA + I R_{\text{BallastTotal}} \quad (4)$$

Where

VA = the voltage across the arc heater

R<sub>BallastTotal</sub> = overall effective resistance which the ballast resistors present to the arc heater circuit

Since VA is the value that is measured in the facility, VB must be solved for by the above equation.

There are eight ballast resistors altogether, one for each of the four electrodes at each end of the arc heater. These adjustable water cooled tubular resistors are for equalizing the current through the electrodes. For consistent electrode performance, lower power runs may use only two or three electrodes at each end of the arc heater. Therefore, to allow for these cases, based upon measurements of the ballast resistors' resistances, R<sub>BallastTotal</sub> is set equal to 0.05 ohms, 0.067 ohms, or 0.1 ohms, depending upon whether the electrode configuration used is 4x4, 3x3, or 2x2, respectively.

$$DT41 = T4 - T1 \quad (5)$$

Due to the piping configuration, T4 cannot be measured directly. It is determined by the following energy balance equation from the measured values.

$$T4 = (mw T3 - mw_{TB} T2) / (mw - mw_{TB}) \quad (6)$$

$$DDT41 = DT41 - DT41o \quad (7)$$

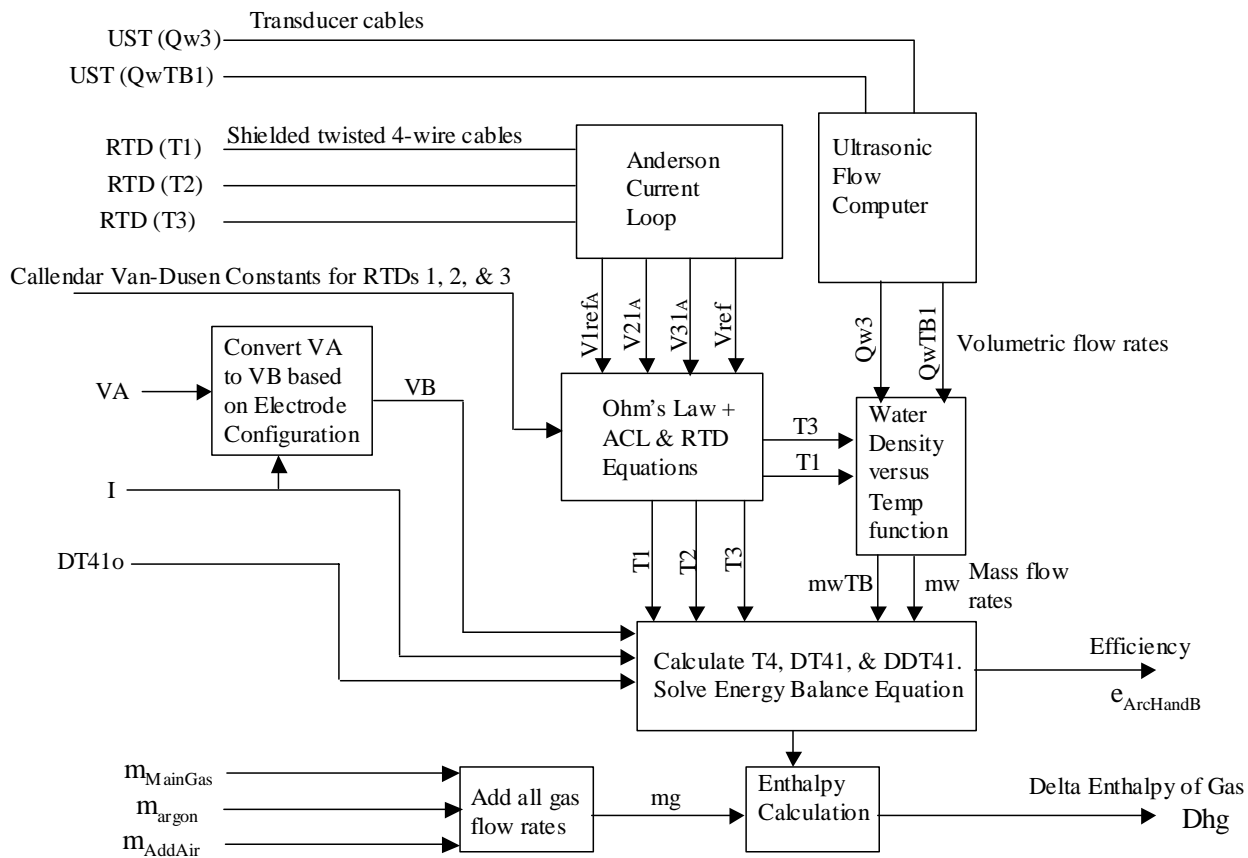
DT41o is the difference between T4 and T1 when the system is at steady state, prior to the arc heater being turned on. It is determined on a run by run basis by analysis of the data. In this way, DDT41

represents the increase in cooling water temperature due solely to the arc heater being on, with the factor of heating due to frictional losses being subtracted.

## CALCULATION OF EFFICIENCY AND DELTA ENTHALPY OF THE GAS

The Instrumentation & Calculation Block Diagram of Fig. 3 is self explanatory, bringing together everything that has been previously covered, showing how all of the measurements taken flow through instruments and calculation blocks to give the answers of efficiency and delta enthalpy of the gas.

All of the equations used are shown in detail in a Mathcad model available from the author.



**FIG. 3 INSTRUMENTATION & CALCULATION BLOCK DIAGRAM**



## UNCERTAINTY ANALYSIS

An uncertainty analysis is performed to determine how the uncertainties in the values measured propagate to uncertainties in the results. The formula for calculating the uncertainty in the result based on the uncertainties in the measurements is elementary, and can be found in most texts on error analysis. In words, the formula is: the uncertainty in the result is the square root of the sum of the squares of the products of the partial derivatives of the function with respect to each variable measured multiplied by the corresponding uncertainty of each variable. (6)

The ASTM Standard gives desired levels of uncertainty for the values measured, and outlines the correct application of uncertainty analysis so as to predict the uncertainty of each result on a case by case basis, where it states on page 4, “Variance analyses of arc test conditions shall provide a sound basis for estimation of the reproducibility of the plasma-arc environment.” (2)

In Table 1 below, the uncertainties that the ASTM Standard specifies are contrasted with estimated uncertainties for the AHF instrumentation in conjunction with the EB2 method.

**TABLE 1 - ASTM STANDARD UNCERTAINTIES VERSUS AHF ESTIMATED UNCERTAINTIES**

| Measured Quantity  | Uncertainties ASTM Standard | Estimated Uncertainties for AHF |
|--|-----------------------------|---------------------------------|
| Arc Voltage  | $\pm 1 \%$                  | $\pm 75$ volts                  |
| Arc Current  | $\pm 1 \%$                  | $\pm 20$ amps                   |
| Total mass flow rate of the gas                                  | $\pm 4 \%$                  | $\pm 4 \%$                      |
| Cooling water flow rate  | $\pm 2 \%$                  | $\pm 4$ kg/s                    |
| Increase in cooling water temperature due to arc heater being on | $\pm 1 \%$                  | $\pm 0.1$ °C                    |

These estimated uncertainties were used in conjunction with the uncertainty propagation formula to calculate the uncertainties for efficiency and delta enthalpy for all results.

The uncertainty results from the runs are discussed in the next section.

The Mathcad model shows all of the equations used to calculate the uncertainties and is available from the author.

## PROCESSING THE DATA

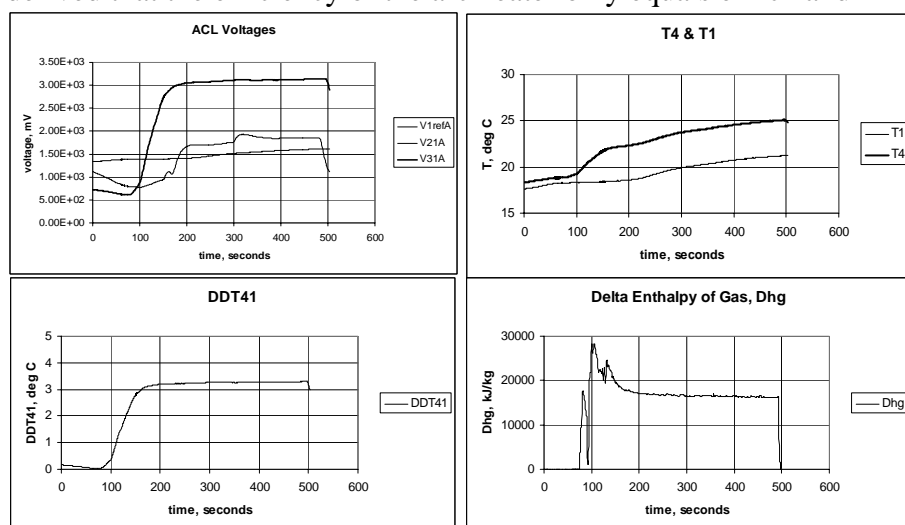
All of the data required for the method are time stamped and digitally recorded during every run. Other arc heater and experimental data are taken as a part of standard procedures. After the run, the data is reduced to a text form and is pasted into a spreadsheet where all of the calculations of the method are

performed for every data point. Graphs of the calculation results are examined to determine the interval(s) where steady-state conditions were achieved. Then the values are averaged over each steady-state interval to generate an operational data point for each interval. Each operational data point is multidimensional and gives the average values of all data taken as well as all calculated results for the interval. A subset of these values from each operational data point is recorded as an entry in a row on a table (spreadsheet), including key running condition data along with the efficiency and delta enthalpy, and their calculated uncertainties.

In many runs the objective is to achieve just one running condition during the run. In other runs, the objective is to achieve multiple running conditions during the run. For example, there was a run in which eight different running conditions were achieved during one run, and there was sufficient steady-state so that eight different operational data points were determined.

Since this data started to be taken in May 2000 through November 2001, a total of 266 runs were made. Of these runs there were 52 in which no enthalpy results were obtained, due to either of three reasons: the run being aborted; insufficient steady-state achieved to make a valid reading; or a computer file error resulting in no EB2 data being taken. However, from these 214 runs with EB2 results, a total of 305 steady-state operational data points were determined. The uncertainty in  $Dh_g$  ranged from  $\pm 5\%$  to  $\pm 82\%$ , with the average being  $\pm 14\%$ . It should be noted that in the case of  $82\%$  uncertainty in  $Dh_g$ , the cause for this is readily apparent since it was a very low power, low enthalpy run, where DDT41 was only around  $0.7^\circ\text{C}$ . This emphasizes the importance of doing an uncertainty analysis for each run, since the running conditions can affect the uncertainty results significantly.

In Fig. 4 the graphical results of DDT41 and  $Dh_g$  from one run are shown for illustration. Table 2 shows the operational data points from this run as well as those from other runs in the same series. Note that the efficiency shown in Table 2 is for the arc heater only, being the ratio of the energy to the gas over the power to the arc heater only (not including the power to the ballast resistors). It is easily derived that the efficiency of the arc heater only equals  $e_{\text{ArcHandB}}$  multiplied by the ratio  $V_B/V_A$ .



**FIG. 4 – GRAPHICAL RESULTS FROM RUN AHF226R026**

**TABLE 2 – OPERATIONAL DATA POINTS FOR AHF RUN SERIES 226**

| AVERAGES OVER TIME INTERVALS INDICATED TO LEFT |         |         |         |        |        |       |         |          |         |         |       |       |       |
|--|---------|---------|---------|--------|--------|-------|---------|----------|---------|---------|-------|-------|-------|
|  |         |         | Uncer-  |        | Uncer- |       |         |          | PA, MW  |         |       |       |       |
|  |         |         | tainty  |        | tainty |       | mg, g/s |          | power   |         | deg C | deg C |       |
|  |         |         | Dhg     | e      |        |       | Total   | consumed | deg C   | deg C   | deg C | deg C |       |
|  |         |         | in      |        | in     |       | gas     | in       | cooling | cooling | DT41o | DT41o |       |
| Averages                                       |         |         | kJ/kg   | Dhg, % | effic. | e, %  |         |          | mass    | arc     | water | water | used  |
| taken  |         |         | Delta H | Plus   | arc    | Plus  | Volts   | Amps     | flow    | heater  | in    | out   | in    |
| Run  | from,   | to,     | of the  | Or     | heater | Or    | Arc     | Arc      | rate    | only    | T1    | T4    | calcs |
| ID   | seconds | seconds | gas     | Minus  | only   | Minus | Voltage | Current  | rate    |         |       |       |       |
| AHF226R001                                     | 360     | 400     | 12005   | 12     | 0.454  | 9     | 2073    | 1386     | 108.8   | 2.87    | 21.5  | 23.9  | 0.600 |
| AHF226R003                                     | 300     | 400     | 14153   | 9      | 0.458  | 6     | 2581    | 1782     | 148.9   | 4.60    | 23.9  | 27.4  | 0.600 |
| AHF226R004                                     | 350     | 400     | 12167   | 9      | 0.457  | 6     | 2793    | 1997     | 209.2   | 5.58    | 19.7  | 23.7  | 0.526 |
| AHF226R005                                     | 400     | 500     | 12984   | 8      | 0.483  | 5     | 3130    | 1977     | 230.1   | 6.19    | 22.7  | 27.0  | 0.566 |
| AHF226R006                                     | 400     | 440     | 14378   | 6      | 0.517  | 3     | 3993    | 2181     | 313.2   | 8.71    | 19.9  | 25.3  | 0.562 |
| AHF226R007                                     | 350     | 400     | 14090   | 10     | 0.490  | 7     | 2321    | 1595     | 128.8   | 3.70    | 21.2  | 23.9  | 0.566 |
| AHF226R008                                     | 400     | 440     | 13868   | 10     | 0.477  | 7     | 2324    | 1611     | 128.8   | 3.74    | 22.2  | 25.0  | 0.527 |
| AHF226R009                                     | 420     | 460     | 14785   | 9      | 0.480  | 6     | 2569    | 1785     | 148.8   | 4.59    | 20.8  | 24.1  | 0.579 |
| AHF226R010                                     | 480     | 520     | 12355   | 8      | 0.472  | 5     | 2765    | 1982     | 209.2   | 5.48    | 20.7  | 24.7  | 0.566 |
| AHF226R011                                     | 460     | 500     | 13977   | 8      | 0.482  | 5     | 3065    | 2183     | 230.7   | 6.69    | 21.4  | 25.9  | 0.556 |
| AHF226R012                                     | 580     | 620     | 14495   | 6      | 0.514  | 3     | 4043    | 2186     | 313.3   | 8.84    | 21.8  | 27.3  | 0.576 |
| AHF226R013                                     | 300     | 400     | 13458   | 10     | 0.469  | 7     | 2339    | 1580     | 128.8   | 3.69    | 24.5  | 27.1  | 0.430 |
| AHF226R014                                     | 500     | 800     | 14005   | 6      | 0.500  | 4     | 4036    | 2175     | 313.2   | 8.78    | 26.1  | 31.6  | 0.590 |
| AHF226R015                                     | 200     | 400     | 13395   | 11     | 0.444  | 8     | 2350    | 1398     | 108.8   | 3.29    | 19.1  | 21.6  | 0.510 |
| AHF226R016                                     | 300     | 400     | 13362   | 11     | 0.436  | 8     | 2401    | 1388     | 108.8   | 3.33    | 21.3  | 23.8  | 0.430 |
| AHF226R017                                     | 200     | 400     | 15678   | 9      | 0.473  | 6     | 2670    | 1600     | 128.8   | 4.27    | 22.8  | 25.8  | 0.492 |
| AHF226R018                                     | 200     | 400     | 15452   | 9      | 0.430  | 6     | 2959    | 1806     | 148.8   | 5.34    | 23.3  | 27.2  | 0.486 |
| AHF226R019                                     | 250     | 450     | 11054   | 9      | 0.426  | 6     | 2733    | 1986     | 209.3   | 5.43    | 22.3  | 26.3  | 0.519 |
| AHF226R020                                     | 400     | 600     | 12860   | 8      | 0.444  | 5     | 3117    | 2002     | 215.6   | 6.24    | 20.2  | 24.6  | 0.562 |
| AHF226R021                                     | 300     | 500     | 14339   | 8      | 0.442  | 5     | 3473    | 2186     | 234.1   | 7.59    | 20.8  | 26.0  | 0.540 |
| AHF226R022                                     | 400     | 500     | 15027   | 6      | 0.454  | 4     | 4718    | 2196     | 313.3   | 10.36   | 22.0  | 28.8  | 0.562 |
| AHF226R023                                     | 200     | 400     | 15258   | 9      | 0.456  | 7     | 2686    | 1605     | 128.8   | 4.31    | 20.9  | 24.0  | 0.555 |
| AHF226R024                                     | 250     | 350     | 14238   | 11     | 0.464  | 8     | 2421    | 1380     | 108.9   | 3.34    | 19.0  | 21.6  | 0.555 |
| AHF226R025                                     | 300     | 400     | 15778   | 9      | 0.472  | 6     | 2716    | 1585     | 128.8   | 4.30    | 16.8  | 20.0  | 0.555 |
| AHF226R026                                     | 350     | 450     | 16408   | 9      | 0.458  | 6     | 2956    | 1802     | 148.8   | 5.33    | 20.7  | 24.5  | 0.562 |
| AHF226R027                                     | 350     | 500     | 12795   | 8      | 0.441  | 5     | 3066    | 1980     | 209.4   | 6.07    | 15.9  | 20.2  | 0.555 |
| AHF226R028                                     | 350     | 450     | 14633   | 8      | 0.446  | 5     | 3455    | 2183     | 230.1   | 7.54    | 17.0  | 22.3  | 0.551 |
| AHF226R029                                     | 300     | 400     | 14232   | 11     | 0.472  | 7     | 2376    | 1381     | 108.8   | 3.28    | 18.8  | 21.2  | 0.499 |
| AHF226R030                                     | 300     | 400     | 11953   | 18     | 0.385  | 14    | 1512    | 1413     | 68.8    | 2.14    | 19.4  | 21.5  | 0.562 |

## JUSTIFICATION FOR USING PIPE SURFACE TEMPERATURE

As mentioned previously, the EB2 method requires that steady-state be attained in order for the results to be valid. At all the points where the cooling water temperatures are measured, the RTDs measuring cooling water temperature are located at points where the water has traveled sufficiently far (more than 20 pipe diameters) in fully developed turbulent flow to be fully mixed, and at uniform temperature.

Heat transfer calculations were performed with standard equations for predicting heat transfer coefficients for both forced convection in pipes and free convection from horizontal cylinders (pipes) to surrounding air. (7) Convective heat transfer coefficients inside the 6 inch schedule 80 pipe on the order of 17000 to 23000 W/(m<sup>2</sup> K) were obtained for a typical water velocity of 12 m/s, over the range of cooling water operating temperature. The highest free convection heat transfer coefficients for the heat

transfer from the outside of the pipes to the surrounding air were less than  $5.7 \text{ W}/(\text{m}^2 \text{ K}) = 1 \text{ Btu}/(\text{hr ft}^2 \text{ }^\circ\text{F})$ . When including the conductive heat transfer through the pipe wall, these calculations show that even at the hottest cooling water temperatures attained (around  $32 \text{ }^\circ\text{C}$ ) the rate of heat transfer from the pipes to the surrounding air is minimal, and that the outer pipe surface temperature would be extremely close to the water temperature inside the pipe so as not to significantly affect the accuracy of the temperature readings. The reason for this is that around 99.8 % of the overall resistance to heat transfer from the inside water temperature to the outer surrounding air temperature is in the free convection heat transfer from the outer pipe surface to the surrounding air. Furthermore, any potential problems from this are totally mitigated by the Styrofoam insulation covering the pipe and RTDs at the measurement points.

Another issue related to the use of the pipe surface temperature is whether the response time (i.e. time constant) there would be low enough to meet the needs of the method for typical run durations of the AHF. In the planning stages of this project, unsteady-state finite element heat transfer analysis was performed to predict the time constant that would be expected at the surface of the pipe. These results showed that the response time should be quick enough. The observed response time results were about twice what was predicted, but are still acceptable. Typical time constants for the pipe surface temperature responding to an immediate change in arc power have been observed to be around 20 seconds. The initial half of this time is what it takes for the downstream RTD to start to register a change in temperature, simply due to the distance downstream where the RTD is located and the thermal mass of the arc heater and pipes. The last half of the time takes the temperature from its initial value to a value 63.2 % of the way toward its final temperature due to the step change in power. The time constant is defined as the time it takes for a response to a step change to reach 63.2 % of the total change that will occur.

## **HEAT LOSSES TO SURROUNDINGS HAVE NEGLIGIBLE EFFECT ON METHOD**

Heat transfer calculations show that at the hottest cooling water temperatures, less than 0.1 % of the heat removed from the arc heater by the cooling water would be lost to the surroundings by free convection from the arc heater and pipe surfaces to the surrounding air. This is one order of magnitude less than the uncertainty specified by the ASTM standard for the delta T of the cooling water,  $\pm 1 \text{ } \%$ . Therefore the assumption of the ASTM standard that heat losses to the surroundings are negligible is valid.

Also, there is a related question of whether the point where the temperature of the overall flow of cooling water from the arc heater is so far downstream that its temperature will have dropped enough due to heat losses to the surroundings that it would significantly affect the validity of the temperature reading at that point. Calculations showed that this was also negligible.

## FUTURE WORK

It is planned to shortly implement the EB2 method in the Interaction Heating Facility (IHF), which is an arc heater rated at 60 MW. Due to the branching of the pipe layout, this facility also will require that two cooling water flow rates be measured, as well as two exiting cooling water temperatures. Since the proposed best locations to measure the flow rates are not optimum in terms of the length of straight run of pipe, dual beam transit-time ultrasonic flow meters will be used. Beyond that it is expected that further implementations will be made for other arc heaters as well, including a small research arc heater. Future work may also involve the analysis and use of the large body of operational data that is now being routinely acquired and archived.

## CONCLUSION

The non-intrusive instrumentation of thin film RTDs with an Anderson Current Loop signal conditioner for the cooling water temperatures, and transit-time ultrasonic flow meters for the cooling water flow rates, proved to be viable options for applying the Enthalpy By Energy Balance method to the AHF.

## REFERENCES

1. Balter-Peterson, A., Nichols, F., Mifsud, B., Love, W., “Arc Jet Testing in NASA Ames Research Center Thermophysics Facilities”, AIAA-92-5041, American Institute of Aeronautics and Astronautics, Washington, DC, 1992
2. “Standard Practice for Measuring Plasma Arc Gas Enthalpy by Energy Balance”, ASTM Standard Designation: E 341-96, American Society for Testing and Materials, West Conshohocken, PA, 1996
3. Anderson, Karl, “Constant current loop impedance measuring system that is immune to the effects of parasitic impedances”, United States Patent 5371469, 1994
4. Anderson, Karl, “Current Loop Signal Conditioning: Practical Applications”, NASA TM-4636, NASA Dryden Flight Research Center, Edwards, CA, 1995
5. Hill, Gerald, “High Accuracy Temperature Measurements using RTD’s with Current Loop Conditioning”, NASA TM-107416, NASA Glenn Research Center (formerly Lewis Research Center), Cleveland, OH, 1997
6. Taylor, John, An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements, 2<sup>nd</sup> Edition, University Science Books, Sausalito, CA 1997
7. Holman, J. P., Heat Transfer, 8<sup>th</sup> Edition, McGraw-Hill, New York, 1997